PB87-145967

Wide Area Ozone Dry Deposition Measurements

(U.S.) Environmental Protection Agency
Research Triangle Park, NC

Jan 87

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1. REPORT NO.	2.	3.
EPA/600/D-87/003		PB87-145967

4. TITLE AND SUBTITLE	5. REPORT DATE
WIDE AREA OZONE DRY DEPOSITION MEASUREMENTS	January 1987
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)	8. PERFORMING ORGANIZATION REPORT NO.
J. M. Godowitch and J.K.S. Ching	
9. PERFORMING ORGANIZATION NAME AND ADDRESS	10. PROGRAM ELEMENT NO.
	A101/B/63/21 1324 (FY-87)
Same as Block 12.	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS	13. TYPE OF REPORT AND PERIOD COVERED
Atmospheric Sciences Research Laboratory--RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	14. SPONSORING AGENCY CODE EPA/600/09

15. SUPPLEMENTARY NOTES

16. ABSTRACT

An experimental study to investigate the temporal and spatial variations of ozone deposition was conducted as part of the Northeast Regional Oxidant Study program in August 1979. Ozone fluctuations and fluxes were obtained from a fast response ozone sensor on-board a research aircraft equipped with gust probes and fast response temperature probe for turbulence measurements. To obtain areal measurements of ozone deposition, low level aircraft runs were performed in the mixed agricultural region around Lancaster, PA and in forested terrain to the northwest.

Statistical results derived from two case study days show a maximum ozone deposition velocity of 0.90 cm/s over the cropland during the early afternoon when convective turbulence was strongest. Ozone flux decreased with height, and it was weaker in a valley compared to a forested ridge due to the presence of a lake along the valley floor. Ozone fluxes were negative during the daytime period in agreement with surface layer tower measurements.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

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U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA. 22161

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS (This Report)	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	5
	20. SECURITY CLASS (This page)	22. PRICE
	UNCLASSIFIED	

EPA/600/D-87/003
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WIDE AREA OZONE DRY DEPOSITION MEASUREMENTS

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1. INTRODUCTION

The treatment of surface dry deposition of pollutants, such as ozone, is an important component of regional-scale air quality simulation models. Deposition rate is generally computed as the product of measurements of pollutant concentration and its deposition velocity. Methods to estimate pollutant deposition have necessarily been based on measurements from micrometeorological techniques at specific sites selected for uniformity of land cover and landscape. Considerable information has been provided from tower measurements about the significant variability in dry deposition of pollutant species in time and for land use types. However, an individual model grid square covers a large area which is likely to contain a mosaic of different land uses and nonuniform terrain. Recent efforts have parameterized deposition velocity as a grid area average value derived from the summation of the contributions from individual land use categories weighted by their fractional coverage within a grid square (Walcek et al., 1986). The effects of inhomogeneities due to multiple land uses, the transition zones between different land use types, and varying roughness and uneven terrain features on grid area deposition needs investigation and anticipated testing of deposition parameterizations in models requires measurements representative of wide areas which exhibit spatially-variable land use and terrain. A suitably instrumented aircraft has provided a valuable measurement platform for area sampling as an extension to and for comparison with point measurements from towers.

The results of analyses of ozone fluxes and deposition velocities derived from aircraft sampling measurements are presented. The flights were conducted during field studies of the NorthEast Regional Oxidant Study (NEROS) program in southeastern Pennsylvania in the region around Lancaster in August 1979. The purpose of the specially designed flight plan was to investigate the spatial and daytime variations of ozone dry deposition from a series of low level horizontal surveys over agricultural cropland, and a forested ridge and valley region. A comparison of the aircraft results with concurrent tower measurements is also made.

*On assignment from the National Oceanic and Atmospheric Administration (NOAA)
U.S. Department of Commerce

2. EXPERIMENT DESIGN AND MEASUREMENTS

Turbulence measurements of the three wind components, air temperature, upward and downward-pointing radiometric temperatures, moisture, and ozone were obtained by a NOAA twin-engine research aircraft which was instrumented with gust probe and aircraft motion systems, and fast response sensors. Details about the aircraft instrumentation and data acquisition system have been documented by Gilmer et al. (1978). The development of a fast response/sensitive ozone instrument adaptable for use in aircraft (Pearson and Stedman, 1980) permitted the measurement of ozone concentration fluctuations and determination of ozone vertical fluxes via the eddy correlation method. The ozone instrument employed the chemiluminescent reaction with nitric oxide method and exhibited an approximate 1 Hz response. All other sensors responded faster than 40 Hz. The on-board data logger system recorded 80 samples s^{-1}, however, the data were reduced to 40 samples s^{-1} during processing. A 5-m separation in the positions of the ozone detector and gust probes caused a time lag of 0.075 s, which was corrected prior to computing the covariance between the ozone and vertical velocity series. Other data processing details have been discussed by Greenhut et al. (1984).

The flight pattern shown in Figure 1 was designed for horizontal areal deposition sampling in the region surrounding Lancaster. The low level horizontal flight paths immediately to the north and east of Lancaster were conducted at about 100 m above relatively level agricultural cropland composed primarily of corn and soybean fields. Despite the predominately rural landscape, the aircraft traversed over numerous small communities and major highways not shown in Figure 1, however, these features were evident as daytime surface "hot spots" from the downward-looking radiometric temperature measurements. After these runs, aircraft transits were made at 600 m MSL to and from the ridge/valley region northwest of Lancaster. A low level run was performed above a forested ridge top and then along the center of an adjacent valley. The segments were from 8 km to over 30 km long.

Measurements with the same type of ozone instrument were also made at 5.2 m on a tower located in a large soybean field near Manheim. Details about these measurements and analysis results have been discussed by Wesely et al. (1982). Additionally, ozone and temperature profiles were obtained from coordinated flights by another research aircraft to give information about the vertical ozone concentration structure and boundary layer height (Z_i).

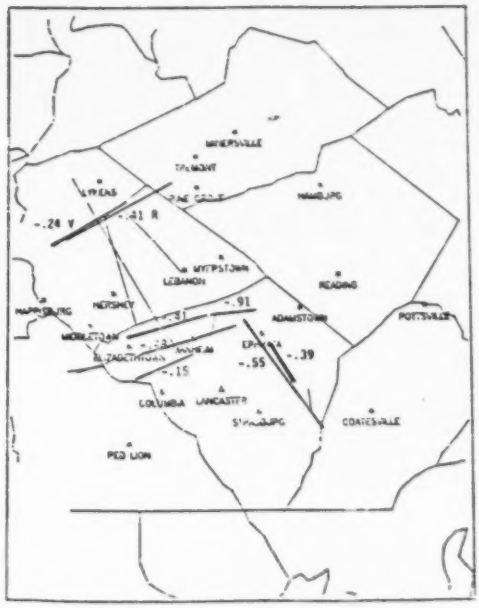

Fig. 1. Flight pattern for wide area ozone deposition measurements in the Lancaster, PA region during NEROS. Numbers next to particular flight legs are ozone fluxes, while R and V represent ridge and valley runs, respectively.

3. DATA ANALYSIS AND RESULTS

The results included herein were taken from analysis of measurements made on August 17 and 20, when three flights were performed during the day. A similar weather pattern existed on both days as the region was under the influence of a high pressure area centered over Pennsylvania. Winds were light at 2-4 m/s from the north to northeast. Fair skies prevailed around Lancaster, however, scattered cumulus clouds formed in the afternoon over the ridge/valley region.

Turbulence measurements of selected parameters from a typical midday flight path over agricultural cropland around Lancaster in Figure 2 indicate a wide variety of scales contributed to the fluctuations. Convective eddies varying in size from tens of meters to over a kilometer are clearly evident in the strong positive fluctuations in the vertical velocity (w) and temperature (T) series, however, much larger scale non-turbulent variations were also present in most parameters, such as in temperature, ozone (Figure 2), and in the horizontal wind components series. The ozone (O_3) measurements, in particular, show greater high frequency fluctuations as noted by Lenschow et al. (1980) due to random noise contamination in the ozone instrument which was reduced by block averaging the data at 1-s intervals prior to computing the ozone variance. Of great concern in this study was the determination of the variances and vertical flux of ozone ($w'O_3'$) when the turbulence signals from the aircraft runs were complicated by the presence of non-turbulent longwave variations and features. Therefore, the turbulence measurements from each flight run were further processed by a two stage high pass running mean filter techique (Greenhut et al., 1984) designed to effectively remove scales greater than about 7 km prior to computing variances and fluxes. The filter technique was preferred to linear or higher order detrending methods, although it is acknowledged that more variance was removed by filtering and the amount of variance removed differed for each parameter.

The results of calculations of ozone fluxes and deposition velocity ($V_d = w'O_3'(z)/O_3(z)$) for the aircraft height above ground (z) are compared to the tower measurements for the same 1-hour period on 2 different days in Table 1. Mean values for the tower were obtained by averaging two 30-minute values, while results for the aircraft were determined from all segments in the agricultural area. The magnitude of the means for $w'O_3'$ were nearly the same for both platforms. Additionally, both sets of ozone fluxes were negative (i.e. toward the surface) at midday in both cases due primarily to ozone uptake by the crops. This comparison provided confidence in the measurements from the aircraft runs. The aircraft mean values for V_d were larger than those for the tower in both cases. Despite the relative agreement in the means, the standard deviations for the aircraft results for $w'O_3'$ and V_d varied from 30% to 50% of their means. In particular, results in parentheses in Table 1 for August 20 also include the value from a flight leg made over an interstate highway (see Figure 1 with a $w'O_3'$ of -0.91) which was about twice the magnitude of most values. Lenschow et al. (1981) also reported large negative ozone flux results from aircraft runs above a major highway and attributed the ozone destruction to NO_x emissions from vehicular traffic. Examinations of ozone time series from these flights revealed large negative O_3 fluctuations and pronounced negative fluxes which corresponded with higher surface temperature signatures suggesting the aircraft flew over small towns or communities. Lenshow et al. (1981) also found noticeable spatial differences in $w'O_3'$ with stronger negative values observed over irrigated farmland than for range land. Thus, real variations in $w'O_3'$, such as those observed for the different segments in Figure 1 can be expected from area measurements and area deposition can be expected to vary for different distributions of surface land cover features.

Evidence of a daytime variation of ozone statistics and deposition parameters derived from all aircraft runs in the agricultural area

Table 1. Aircraft (A) / Tower (T) Comparison of Ozone Deposition Parameters

Date	8/17		8/20		
Time (LDT)	1200		1200		
	T	A	T	A	
$w'O_3'$ (ppb m/s)	-0.37	-0.36 ±0.10	-0.35	-0.35 ±0.17	(-0.43 (±0.26)
V_d (cm/s)	0.82	0.96 ±0.31	0.62	0.65 ±0.33	(0.83) (±.55)
O_3 (ppb)	45.2	37.6 ±3.4	57.0	52.8 ±5.4	
S_{O3}(ppb)	6.1	0.9 ±0.3	8.1	1.2 ±0.5	
N	2	7	2	6	(7)

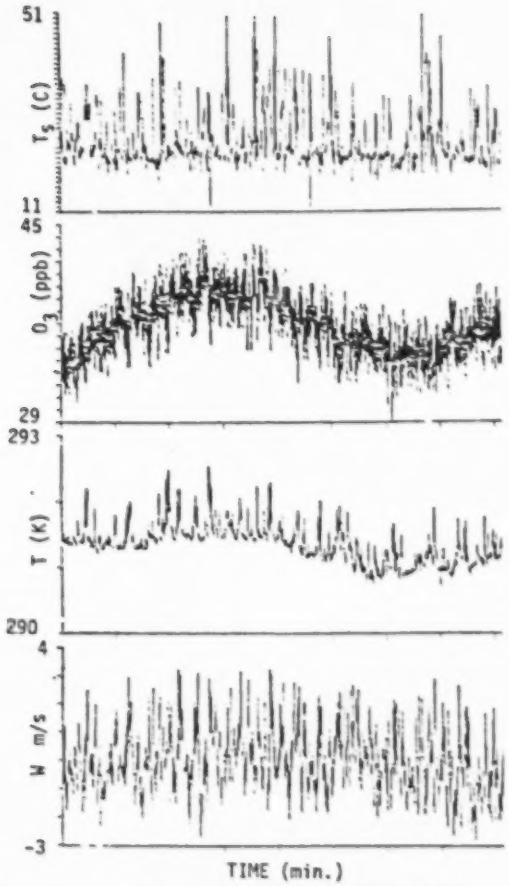

Fig. 2. Turbulence measurements of vertical velocity, (w), temperature (T), ozone (O_3), and radiometric surface temperature (T_s) starting at 1228 local time on 17 August 1979 at 100 m AGL over mixed agricultural cropland near Lancaster, Pennsylvania. Each minute corresponds to 4 km.

is given in Table 2. Results from morning flights (0800) show small vertical velocity standard deviations (S_w) and weak ozone flux, since convective turbulence had not yet destroyed the nocturnal inversion at the aircraft altitude. Tower measurements of O_3 concentration at this time were even lower due to ozone loss during the stable conditions overnight. The results for 1200 under highly convective conditions for a normalized height of $0.1Z_i$ show a higher O_3 concentration, and the mean values of $w'O_3'$ and V_d increased to -0.39 and 0.90, respectively. Standard deviations were about 50% of the mean values. There was a slight decrease in V_d by 1600, even though $w'O_3'$ was larger than at 1200 because of a greater value of O_3 concentration.

There is a notable difference of ozone flux with height disclosed in Table 2 which is indicative of strong vertical flux divergence of ozone. The low level results at $0.1Z_i$ were 50% greater in the mean than those derived from runs at $0.4Z_i$. Assuming the magnitude of ozone vertical flux decreased continuously upward

Table 2. Statistical results from aircraft deposition runs over agricultural area surrounding Lancaster, Pa.

Time (LDT)	0800	1200	1300	1400
Z (m AGL)	114.±13.	114.±13.	397.±51.	102.±25.
Z/Z_i	>1	0.11	0.40	0.1
$\overline{w'O'_3}$(ppb m/s)	-.09±0.1	-0.39±.19	-0.20±.18	-0.49±.15
V_d (cm s^{-1})	0.33±.31	0.90±.42	0.44±.43	0.78±.23
O_3 (ppb)	33.1±6.2	45.2±9.7	48.3±9.8	63.2±5.2
S_{O3} (ppb)	1.9±1.6	1.1±0.4	0.9±0.4	1.9±0.5
S_w (m s^{-1})	0.3±0.1	0.8±0.1	1.0±0.2	0.7±0.1
N	16	14	10	12

Table 3. Ozone Deposition and Turbulence Parameters for Ridge (R) and Valley (V) Runs

Date	8/17		8/20	
	R	V	R	V
Time	1340	1350	1328	1340
$\overline{w'O_3'}$	-0.38	-0.28	-0.41	-0.24
V_d	0.84	0.60	0.76	0.47
O_3	45.6	47.1	53.6	51.1
S_{O3}	0.69	0.89	0.82	1.04
S_w	0.98	0.77	1.04	0.34
H(w/m^2)	180.	65.	122.	15.7
S_{Tdn}	1.76	1.80	1.16	1.08
S_{Tup}	2.69	13.05	22.15	20.44
Z/Z_i	0.09	0.11	0.12	0.06

from the surface in the lower part of the mixed layer, a surface value extrapolated from the two aircraft flight levels is near -0.5, which is about 40% larger than the tower mean value of -0.36 derived from both cases. For this situation, surface O_3 deposition derived from area sampling is estimated to be greater than that from a single point measurement when consideration is taken for the observed vertical variation of $w'O_3'$.

The large standard deviation of $w'O_3'$ at $0.4Z_i$ in Table 2 also indicates that the variability is large. While these results and ozone profiles at this time showed O_3 concentration was nearly uniform in the mixed layer, concentrations above Z_i were slightly lower (about 2-4 ppb) on the 17th and about 10 ppb lower on the 20th. Entrainment processes could produce positive O_3 fluxes in the upper part of the mixed layer and might account for the scatter in these measurements.

The forested ridges and valleys northwest of Lancaster present a sharp departure in land use character (cover and topography) when compared with the agricultural fields around Lancaster. There are a series of parallel ridges and valleys in this part of the Blue Ridge mountain chain extending into Pennsylvania. Flight runs were made along the top of the first deciduous forested ridge and at a comparable altitude above the floor of an adjacent valley. The ridge crests were about 450 m MSL and the valley floor was 210 m MSL. There were not enough runs to compute statistics comparable to those for the agricultural area. However, detailed examinations of the ridge/ valley runs provide interesting insight into differences in ozone deposition and turbulence variables. Table 3 contains paired results of afternoon runs made from 1300 to 1400 LDT which were performed at about the same normalized height above the terrain on both case study days. The ozone flux and V_d were greater over the ridge in both runs. In addition, the sensible heat flux (H) and S_w were larger indicating greater turbulence production over the ridge than along the center of the valley. The lower ozone deposition and turbulence fluxes in the valley are attributed to the presence of a lake situated

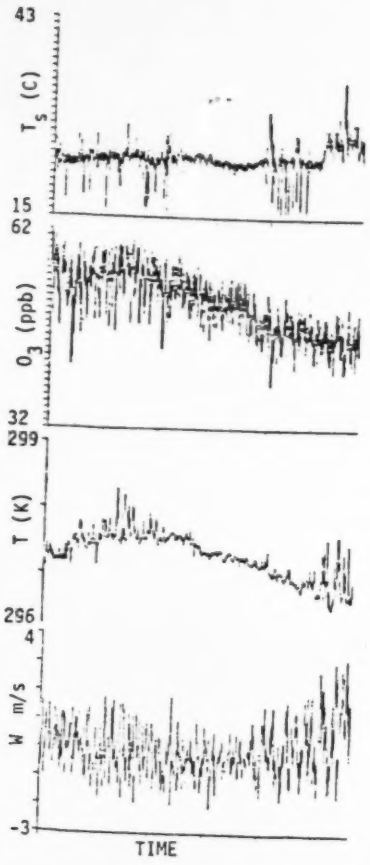

Fig. 3. Same as Fig. 2. except for a valley run on the afternoon of 20 August. A lake, 10 km long, is situated in the center of this segment.

in the center of the valley. The lake was about 10 km long, representing over 30% of the run length. There were markedly weaker fluctuations in the w and T signals, and little surface temperature (T_s) variation (Figure 3) in the section of the valley run identified as above the lake compared to stronger turbulent fluctuations in sections over forested or marshy land in the remainder of the time series. Lenshow et al. (1982) also found significantly lower ozone deposition over water than for forested land. There were also scattered clouds present during these runs which were evident from the warm spots in the upward-looking radiometric temperature series and its large standard deviation (S_{Tup}). However, it does not appear that these would influence the qualitative differences between the ridge and valley runs since the amount of cloud cover on the 20th was about the same (e.g. S_{Tup} was nearly the same for both runs), while the cloud amount on the 17th was small. Thus, the fractional area composed of water bodies is expected to strongly impact ozone deposition in a region.

4. DISCUSSION

This study was an initial attempt to examine wide area dry deposition by aircraft sampling. Further research experiments are needed to examine pollutant dry deposition over various representative land cover areas under different meteorological conditions for comparison with point measurements and for the evaluation of model deposition parameterizations.

This initial analysis of a rather limited, but interesting data set shows large spatial variations in ozone dry deposition suggesting the influence of land use differences and topographic features. Subsequent analyses and additional experimental studies are needed to assess the significance and magnitude of different land use distributions on the parameterization of dry deposition in regional scale models or equivalently, on the representativeness of point measurements of pollutant fluxes in regions where land cover variations and surface irregularities are pronounced. The relevant question remains as to the generality of parameterizing deposition velocity by simple linear apportionment with land use coverages in a large grid area.

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Disclaimer - Although the research described in this article has been supported by the U.S. Environmental Protection Agency, it has not been subjected to Agency review and therefore does not necessarily reflect the views of the Agency and no official endorsement should be inferred.